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FLUID FLOW THROUGH POROUS MEDIA. PART II. POROSITY, PERMEABILITY AND AVERAGE GRAIN SIZE OF CONSOLIDATED SANDS*

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ABSTRACT Permeabilities, porosities and particle size distribution curves of twenty-three sand core samples were obtained. It was observed that with increase in the average particle diameter the porosity at first increased and then tended to attain a constant limiting value. Permeability, K, on the other hand increased continuously with the average diameter, d, and the approximate relation $K \propto d^2$ was obtained.

INTRODUCTION

A previous paper[1] dealt with the question of measuring true permeability of sand cores using gases. Measured permeabilities were found to diminish with an increase in the rate of flow and results obtained using hydrogen were higher than those obtained with oxygen. Preliminary measurements using liquids† showed that the latter gave lower permeabilities than those obtained using gases without any correction.

In the present paper relations between permeability, porosity and average grain size of twenty-three sand cores have been studied.

EXPERIMENTAL

The core samples used in these experiments were obtained from four different oil wells. Permeabilities were measured by finding the rate of flow of dry oxygen at low pressure gradients and constant temperature and were calculated from the formula :–

$$K = \frac{2Vp\eta L}{(p_2^2 - p_1^2)A}, \tag{1}$$

where V is the volume of gas flowing per unit time at atmospheric pressure p, p_2 the pressure of the entering and p_1 that of the issuing gas, η is the viscosity of the gas at the temperature of the measurement, L is the thickness and A is the

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† This work was interrupted by the Japanese invasion but may be continued elsewhere later.

cross-section of the cylindrical core. The permeability values were not corrected for any error, *e.g.*, due to slip or kinetic energy effect[1] since approximate values were considered to be sufficiently accurate for present purposes.

Porosities were determined by Melcher's method.[2]

Particle-size distribution curves were drawn from data found using Puri's Siltometer.[3] The curves generally showed one maximum, but occasionally there were two maxima. Representative curves of the two different types are shown in figure 1

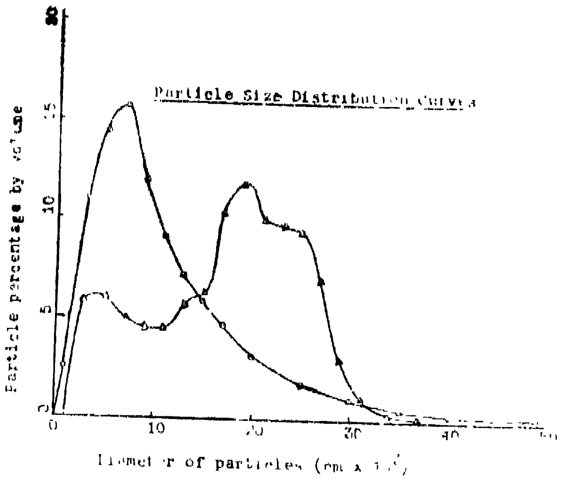

Figure 1

Average grain diameter, $\bar{d}$ was calculated from the particle-size distribution curves from the relation

$$\bar{d}=\left(\frac{100}{\Sigma P_i/d_i^3}\right)^{1/3}, \qquad \dots \quad (2)$$

where P_i is the percentage, by volume, of particles having diameter d_i. Since the value of $\bar{d}$ is mainly determined by the percentage of smaller particles, a smaller value of $\bar{d}$ indicates the presence of a large percentage of particles having diameters smaller than 0.002 cm.

RESULTS AND DISCUSSION

The relation between the average effective diameter and the porosity, f, is shown in figure 2 and that between the diameter and the permeability on a log-log scale in figure 3.

Figure 2 gives a more or less 'S' shaped curve. The porosity appears to attain a constant limiting value at very large particle diameters. This maximum value of the porosity is 22.5 %. It is of interest to note in this connection that when spherical particles of uniform size are arranged to build a hexagonally close-packed structure the porosity equals 25.95%. Other types of arrangements show higher porosities.

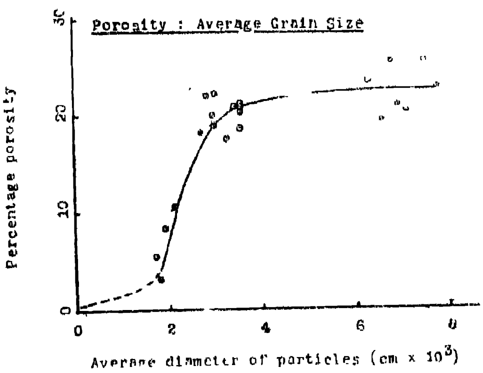

Figure 2

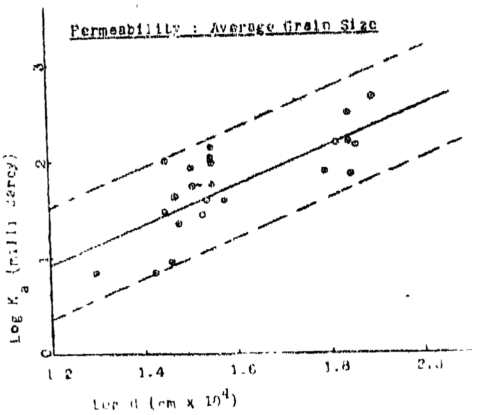

Figure 3

When the particle diameter tends to become negligibly small, porosity also tends to be very small. It may be considered that when $\bar{d}$ approaches zero, f assumes a lower limiting value. The curve can be represented by an equation of the type :—

$$\frac{f-f_{\text{min.}}}{f_{\text{max.}}-f}=d^{n}, \qquad \ldots \quad (3)$$

where f is the porosity corresponding to the average diameter $\bar{d}$, $f_{\text{max.}}$ and $f_{\text{min.}}$ are the maximum and minimum porosities and n is a constant. The value of n appears to be nearly 6 in this particular instance.

The variation of porosity with the average diameter can be explained only when the size and shape of the particles and their spatial arrangements are known. For example, fine particles, if present in appreciable amount, will cement the pores formed by the arrangement of the bigger particles. Further, small particles in sand are generally less symmetrical than the big ones, and when closely packed, will provide a sand with lower porosity. It appears that no experimental work on this topic, using consolidated oil-sands, has yet been reported.

The points plotted in figure 3 fall on a very broad band indicated by the dotted lines. Assuming that log K varies linearly as log $\bar{d}$, the slope of the statistical line drawn through the points is 2.05 which shows that the empirical relation

$$K=\text{Const. } \bar{d}^{2}, \qquad \ldots \quad (4)$$

where K is the permeability corresponding to the average diameter d, is approximately obtained. When the spatial arrangement of the particles is not altered, the permeability of a system containing spherical particles of uniform size will diminish as the square of the diameter of the particles. The scattering of the points in figure 3 from the straight line might be due to a variation in the shape and size of the particles and to their spatial arrangements. The individual effects of these factors cannot be discussed until further measurements have been carried out.

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